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A synchrotron superbubble in the IC 10 Galaxy: a hypernova remnant?

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ABSTRACT

The nature of the synchrotron superbubble in the IC 10 galaxy is discussed using the results of our investigation of its ionized gas structure, kinematics, and emission spectrum from observations made with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences, and based on our analysis of the radio emission of the region. The hypernova explosion is shown to be a more plausible mechanism of the formation of the synchrotron superbubble compared with the earlier proposed model of multiple supernova explosions. A compact remnant of this hypernova may be identified with the well known X-ray binary X-1 – an accreting black hole.

Key words: ISM: bubbles – ISM: kinematics and dynamics – supernova remnants galaxies: individual: IC 10.

1 INTRODUCTION.

The synchrotron superbubble in the IC 10 galaxy was discovered by Yang & Skillman (1993). They associated it with the explosion of about ten supernovae. The synchrotron nature of the radio emission of this superbubble is corroborated by the high degree of its polarization (Chyzy et al. 2003). The multiple supernova explosions model was also adopted by Bullejos & Rozado (2002) and Thurow & Wilcots (2005).

We provided a detailed study of the structure, kinematics, and emission spectrum of the ionized gas in the region of the synchrotron superbubble based on observations made with the 6-m telescope of the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS). We suggest, in accordance with our observations and based on our analysis of the radio emission of the region, that the synchrotron superbubble was produced by a hypernova explosion and not via multiple supernova explosions as was believed until now.

2 RESULTS OF OBSERVATIONS.

We observed the ionized gas in the synchrotron superbubble region with the SAO RAS 6-m telescope using SCORPIO focal reducer (Afanasiev & Moiseev 2005) operating in three modes: direct [SII]-lines images, long-slit spectroscopy, and observations with a scanning Fabry–Perot interferometer (FPI) in the Hα line. We report the detailed results of our observations in a separate paper (Lozinskaya et al. 2007). In this Letter we summarize the main results of these observations and the ensuing conclusions.

Fig. 1 shows the resulting [SII]6717+31Å lines image of the region with 20-cm continuum radio emission contours from Yang & Skillman (1993) superimposed. Compared to Hα images (from Gil de Paz, Madore & Pevunova (2003) or from our FPI data), our continuum-subtracted [SII] image reveals the most well-defined filamentary shell which one can identify with the synchrotron superbubble.

The size of the filamentary [SII] shell is about 44″, which corresponds to 170 pc at the distance of 790 kpc (Vacca, Sheehy & Graham 2007). Its central coordinates [$\alpha_{(2000)} = 0^h20^m29^s$, $\delta_{(2000)} = 59^\circ16'40''$] agree with those of the radio shell observed by Yang & Skillman (1993).

Our long-slit spectra are indicative of the enhanced [SII] emission in the synchrotron superbubble area, much stronger than in other star-forming regions in the galaxy. Indeed, the I([SII])/I(Hα) ratio in the superbubble lies in the $0.6 - 1.0$ interval (see Fig. 2) and this is consistent with the corresponding ratios of supernova remnants (SNRs). Fig. 1 in Rosado et al. (1999) and fig. 4 in Hidalgo-Gamez (2005) also point to the bright [SII] emission in the region.

We have performed a very detailed Hα line study of the kinematics of ionized gas using a scanning FPI, and analysed more than 40 position-velocities (P-V) diagrams crossing the synchrotron superbubble in various directions. The FPI data allowed us to estimate the characteristic expansion velocity

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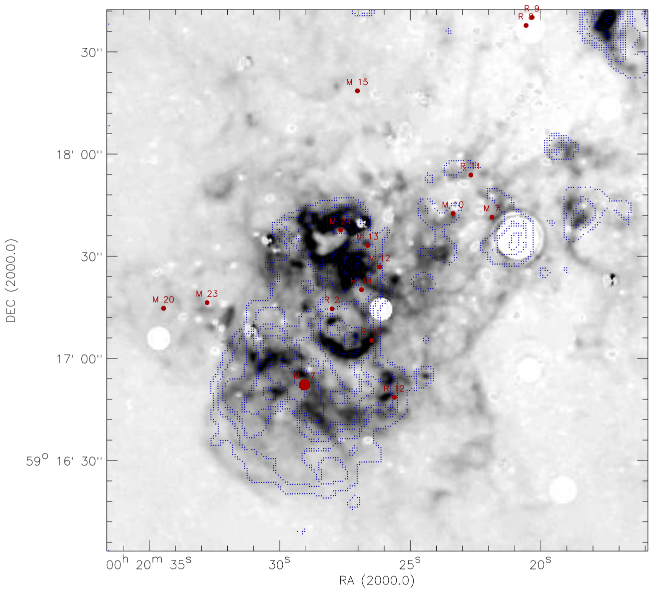

Figure 1. The [SII]6717+31Å lines image of the region taken with the 6-meter telescope of the SAO RAS with SCORPIO focal reducer. Small red circles show spectroscopically confirmed WR stars. The large red circle in the South-eastern part of the region is the WR star M17, a component of the brightest compact X-ray source X-I in the IC 10 galaxy (see text). The blue lines show the superimposed 20-cm continuum radio emission contours from Yang & Skillman (1993).

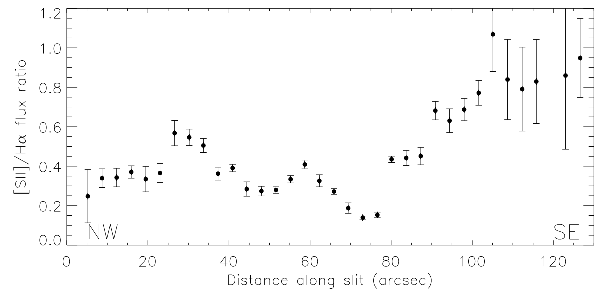

Figure 2. The variations of [SII]/Hα flux ratio along the spectrograp slit. The position angle of the slit was $PA = 133°$. The synchrotron superbubble correspods to the distances $90-130$ arcsecs.

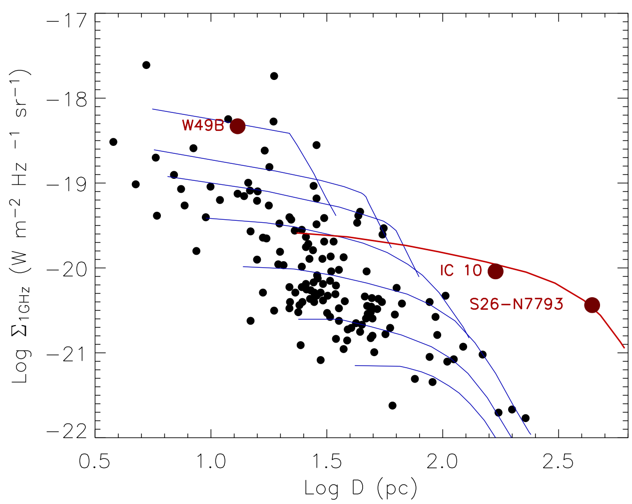

Figure 3. The $\Sigma_{1GHz} - D$ diagram mainly based on data extracted from fig. 6 in Asvarov (2006). The black dots show the position of SNRs in our Galaxy and several nearby galaxies. The red circles mark the position of the hypernova remnant candidates including the synchrotron superbubble in IC 10. The red line is the theoretical $\Sigma - D$ relation constructed by Asvarov (2006) for the hypernova explosion with the initial energy of $E_) = 5 \times 10^{52}$ erg in a medium with unperturbed density $n_0 = 0.01$ cm^{-3}. The blue curves in the figure show the $\Sigma - D$ dependences for supernova remnants with standard energy $E_0 = 10^{51}$ erg expanding in media of different densities.

of the system of bright knots and filaments to be 50 – 80 km s^{-1}. The measured expansion velocity fully agrees with the 50–70 km s^{-1} value mentioned by Bullejos & Rozado (2002).

We use the above expansion velocity, combined with the electron density of $n_e \simeq 20 - 30$ cm^{-3} estimated from the [SII]6717/6731Å emission lines ratio, to evaluate the mass and kinetic energy of the optical shell to be about $M \simeq 8 \times 10^{38}$ g and $E_{kin} \simeq (1-3) \times 10^{52}$ erg, respectively. (As is commonly adopted for SNRs, we assume that the shell thickness is about 0.1 of its radius.)

The energy obtained is between the value of $E_{kin} \simeq (5-6) \times 10^{52}$ erg estimated by Thurow & Wilcots (2005) from the mean halfwidth of the Hα line in the synchrotron superbubble, and $E_{kin} \simeq (0.6-1.2) \times 10^{51}$ erg reported by Bullejos & Rozado (2002) and Rosado et al. (2002).

3 THE NATURE OF THE SUPERBUBBLE

The kinetic energy of an old SNR is lower than about 30 per cent of the SN explosion energy (Chevalier 1974). Thus our inferred kinetic energy for the optical shell in the synchrotron superbubble corresponds to the explosion of about dozen supernovae plus stellar winds of their host OB association, or to a hypernova explosion.

However, our analysis of the synchrotron radiation of the superbubble leads us to suggest that a hypernova explosion explains better the nature of this radiation than do multiple supernovae.

First, the surface brightness $\Sigma_{(1GHz)} = 10^{-20}$ W m^{-2} Hz^{-1} sr^{-1} for the size of superbubble of $170-190$ pc fits perfectly well the theoretical $\Sigma(D)$–dependence that Asvarov (2006) derived for a hypernova explosion with the initial energy of $E_0 = 5 \times 10^{52}$ erg in a medium with density $n_0 = 0.01$ cm^{-3} (see Fig. 3 where we show the superbubble in IC 10 by a red circle).

Second, and this is most important, we are the first

to allow for the fact that explosions of 'recent' supernovae in the model of Yang & Skillman (1993) occur in a tenuous cavity inside the common shell swept out by the 'first' supernovae.

The first few SN explosions may indeed have produced several times stronger radio emission compared to that of a single SN. However, the situation changes radically as the first SNe create the common swept-out supershell. The remnants of subsequent SNe expand in a low-density medium inside the swept-out cavity, and their radio emission rapidly decays because of the adiabatic expansion of the cloud of relativistic particles with magnetic field.

The radio brightness of a SNR depends on the parameters of the ambient medium as

$$\Sigma(D) \propto n_0^{2/3} B_0^{1.5} \propto n_0^{2/3+1.5k_0},$$

where $B_0 \propto n_0^{k_0}$ (Asvarov 2006).

The brightness of an SNR in the cavity where the density is 10 or 100 times lower than the ambient density can be easily seen to decrease by a factor of 5 or 20, respectively.

The allowance for the fact that the interstellar magnetic field is frozen in the gas further strengthens this conclusion, because the magnetic field inside the cavity is weaker than the ambient field. Correspondingly, the surface radio brightness of the SNR in the tenuous cavity mentioned above decreases by a factor of several tens or several hundred.

Of course, these are just qualitative estimates, because some SNe may explode in the dense medium near the swept-out shell.

We nevertheless conclude that subsequent SN explosions in the model of Yang & Skillman (1993) contribute little to the radio brightness of the synchrotron shell created by the first SN explosions, implying a further increase of the required number of supernovae. That is why we believe a hypernova explosion to be a more plausible mechanism for the formation of the synchrotron superbubble than multiple supernova explosions.

The age of this hypernova remnant determined by its size and the expansion velocity of 50-80 km s^{-1} inferred in this paper corresponds to $t \simeq (4-7)\times 10^5$ yr if it is at the Sedov stage or $t \simeq (3-5)\times 10^5$ yr for the case of the radiative cooling stage.

Such an age also supportive of the hypernova hypothesis, because ten supernova explosions require about 2 orders of magnitude longer time.

The anomalously high number of Wolf-Rayet (WR) stars in the galaxy IC 10 provides indirect evidence in support of the same conclusion. In the case of a normal IMF the anomalously high density of WR stars implies virtually 'simultaneous' current burst of star formation covering most of the galaxy (see, e.g., Massey et al. (2007) and references therein). We 'caught' IC 10 during the short stage of its evolution when massive WR progenitors are still alive, but the supermassive pre-hypernova has already finished its life, and we observe the remnant of its explosion as the synchrotron superbubble.

One can believe the compact remnant of this hypothetical hypernova to coincide with the brightest X-ray source in the galaxy X-I, discovered by Brandt et al. (1997). X-I is a stellar-mass black hole accreting from WR star M17; the mass of this black hole is $\simeq 4M_\odot$ if it is not spinning, or up to ≈ 6 times higher if there is significant spinning (Bauer & Brandt 2004; Wang et al. 2005).

If the synchrotron shell is indeed a hypernova remnant, one would expect to find an extended X-ray emission in the region. Based on *CHANDRA* observations, Bauer & Brandt (2004) found evidence for faint extended X-ray emission 'cospatial' with the synchrotron superbubble. However, accurate reduction of *XMM-Newton* and *CHANDRA* observations (removing the X-ray CCD-readout streaks of X-I) led Wang et al. (2005) to conclude that the faint diffuse thermal X-ray emission appears to be associated with the intense star-forming region. New X-ray observations are highly desirable.

4 DISCUSSION AND CONCLUSION.

Compared to the other two hypothetical hypernova remnants — W49B and S26-N7793 — shown in Fig. 3 the synchrotron supershell in IC 10 appears to be the most confidently identified object. Indeed as Keohane et al. (2006) show in their paper, the progenitor of W49B was a supermassive star. At the same time, the location of the radio source in the $\Sigma - D$ relation agrees excellently with the results of the computations that Asvarov (2006) performed for a SN remnant with a standard energy of $E_0 = 10^{51}$ erg in a medium with density $n_0 = 5$ cm^{-3}.

The hypernova remnant S26-N7793 in the NGC7793 galaxy was also earlier attributed to multiple supernova explosions (see Pannutti et al. (2002) and references therein). This S26-N7793 remnant is most probably at a later evolutionary stage than the Synchrotron Shell in IC 10. However, we still do not understand its shape: it appears as an SNR with a long filament as an extension.

NGC 5471B in the galaxy M 101 is one of most reliably identified hypernova remnant (Wang 1999) and was studied in detailed in radio, optical and X-ray ranges (see Skillman (1985), Chu & Kennicutt (1986), Chen et al. (2002) and also references therein). Its kinetic energy reaches $E_{kin} = 5\times 10^{51}$ erg ($E_0 \geqslant 10^{52}$ erg), kinematic age is no more than 10^5 yr, it is characterized by high [SII]/Hα ratio. The one problem of its identification is that NGC 5471B lies in an active star formation region in the giant HII complex NGC 5471 and contains a large number of faint clusters and two clusters as rich as R136 within the bright [SII]-shell NGC 5471B (Chen et al. 2005).

The synchrotron superbubble in the IC 10 does not have this difficulty. Hunter (2001) has distinguished two clusters near the southern border of the superbuble: 4-6 and 4-7. However these are not richest clusters in the galaxy and they could not host dozen supernova explosions.

Note in conclusion that the synchrotron superhshell in IC 10 can be identified as a hypernova remnant based on a combination of several criteria — first, very high kinetic energy of the shell; second, the presence of a bright extended spherically symmetric source of synchrotron radio emission, which is difficult to explain by multiple supernova explosions; third, the optical shell with high [SII]-line brightness, which is "cospatial" with the radio source and has a kinematical age of $t \simeq (3-7)\times 10^5$ yr, and, fourth, the presence of a compact remnant of the explosion of a very massive star.

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REFERENCES

Afanasiev V.L., Moiseev A.V., 2005, Astronomy Letters, 31, 194 (astro-ph/0502095)
Asvarov A.I., 2006, A&A, 459, 519
Bauer F.E., Brandt W.N., 2004, ApJ, 601, L67
Brandt W.D., Ward M.J., Fabian A.C., Hodge P.W., 1997, MNRAS, 291, 709
Bullejos A., Rozado M., 2002, Rev.Mex.A.A. (Serie de Conferencias), 12, 254
Chen C.-H.R., Chu Y.-H., Gruendl R., Lai S.P., Wang Q.D., 2002, AJ, 123, 2462
Chen C.-H.R., Chu Y.-H., Johnson K.E., 2005, ApJ, 619, 779
Chevalier R.A., 1974, ApJ, 188, 501
Chu Y.-H., Kennicutt R.C., 1986, ApJ, 311, 85
Chyzy K.T., Knapik J., Bomans D.J., Klein U., Beck R., Soida M., Urbanik M., 2003, A&A, 405, 513
Gil de Paz A., Madore B.F., Pevunova O., 2003, ApJS, 147, 29
Hidalgo-Gamez A.M., 2005, A&A, 442, 443
Hunter D.A., 2001, ApJ, 559, 225
Keohane J.W., Reach W.T., Rho J., Jarrett T.H., 2006, ApJ, 654, 938
Lozinskaya T.A., Moiseev A.V., Podorvanyuk N.Yu., Burenkov A.N., 2007, submitted to Astronomy Letters
Massey P., Olsen K., Hodge P., Jacoby G.H., McNeill R., Smith R., Strong Sh., 2007, AJ, 133, 2393
Pannuti T.G., Duric N., Lacey C.K., Ferguson A.M.N., Magnor M.A., Mendelowitz C., 2002, ApJ, 565, 966
Rosado M., Bullejos A., Valdez M., Georgiev L., Lacey C., Borissova J., Esteban C., 1999, in Y.-H. Chu, N. Suntzeff, J. Hesser, D. Bohlender, eds., Proc. IAU Symp. 190, New Views of the Magellanic Clouds, Astron. Soc. Pac., San Francisco, p. 168
Rosado M., Valdez-Gutierrez M., Bullejos A., Arias L., Georgiev L., Ambrocio-Cruz, P., Borissova J., Kurtev R., 2002, in Margarita Rosado, Luc Binette, and Lorena Arias, eds., ASP Conf. Ser. 282, Galaxies: The Third Dimension, Astron. Soc. Pac., San Francisco, p. 50
Skillman E.D., 1985, ApJ, 290, 449
Thurow J.C., Wilcots E.M., 2005, AJ, 129, 745
Vacca W.D., Sheehy C.D., Graham J.R., 2007, ApJ, 662, 272
Wang Q.D., 1999, ApJ, 517, L27
Wang Q.D., Whitaker K.E., Williams R., 2005, MNRAS, 362, 1065
Yang H., Skillman E.D, 1993, AJ, 106, 1448